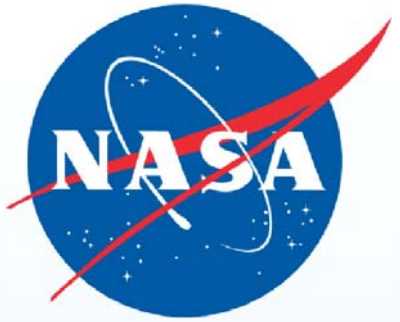
National Aeronautics and Space Administration



Criticality of Low-Energy Protons in Single-Event Effects Testing of Highly-Scaled Technologies

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To be presented by Jonathan A. Pellish at the Single Event Effects (SEE) Symposium and the Military and Aerospace Programmable Logic Devices (MAPLD) Workshop, La Jolla, CA, May 19-22, 2014.

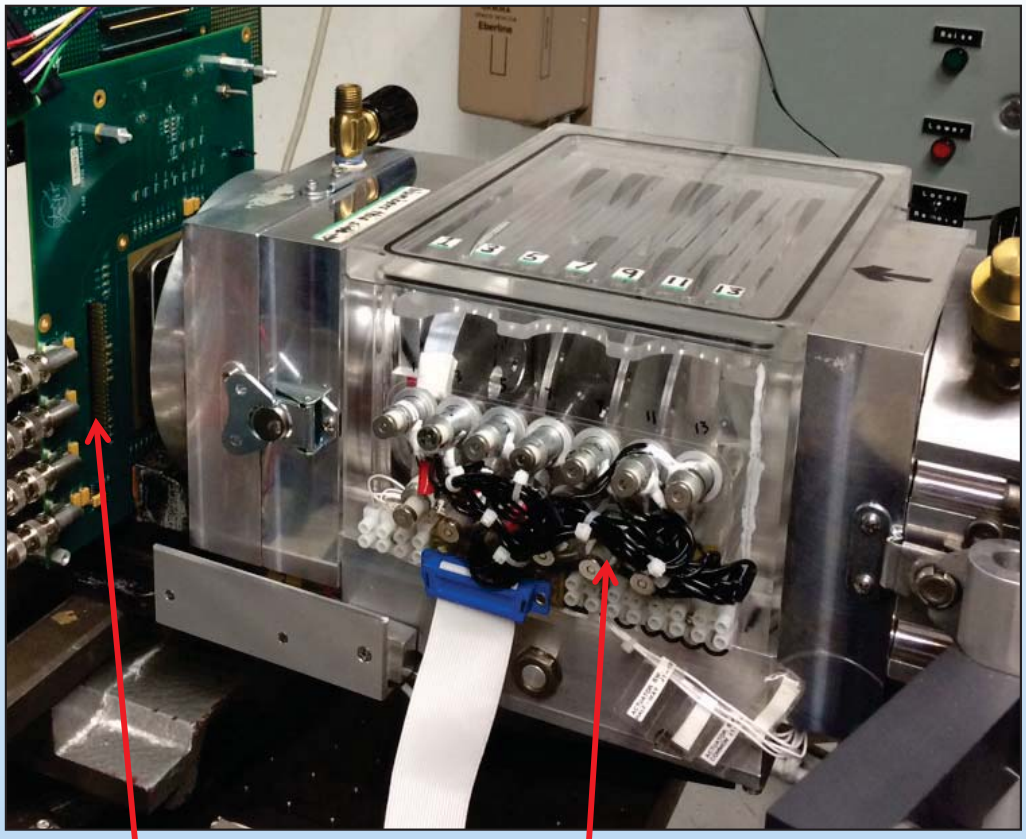
Acronyms

- CMOS: complementary metal oxide semiconductor
- CNL: Crocker Nuclear Laboratory
- CSDA: continuous slowing down approximation
- DBU: double-bit upset
- DUT: device under test
- IBM YKT: Yorktown Heights, NY
- ICRU: International Commission on Radiation Units & Measurements
- IEEE: Institute of Electrical and Electronics Engineers
- IUCF: Indiana University Cyclotron Facility
- LBNL: Lawrence Berkeley National Laboratory
- LEP: low-energy proton
- MCU: multi-cell upset (errors not necessarily in the same data word)
  - Different from multi-bit upset (MBU)
- NIST: National Institute of Standards and Technology
  - ASTAR and PSTAR are NIST tools, not acronyms
- NPTC: Northeast Proton Therapy Center
- SBU: single-bit upset
- SEEM: secondary electron emission monitor
- SEU: single-event upset
- SOI: silicon on insulator
- SRAM: static random access memory
- SRIM: Stopping and Range of Ions in Matter (software program)
- TNS: Transactions on Nuclear Science
- TRIUMF: not an acronym – formerly the Tri-University Meson Facility, Vancouver, Canada
- UC Davis: University of California at Davis

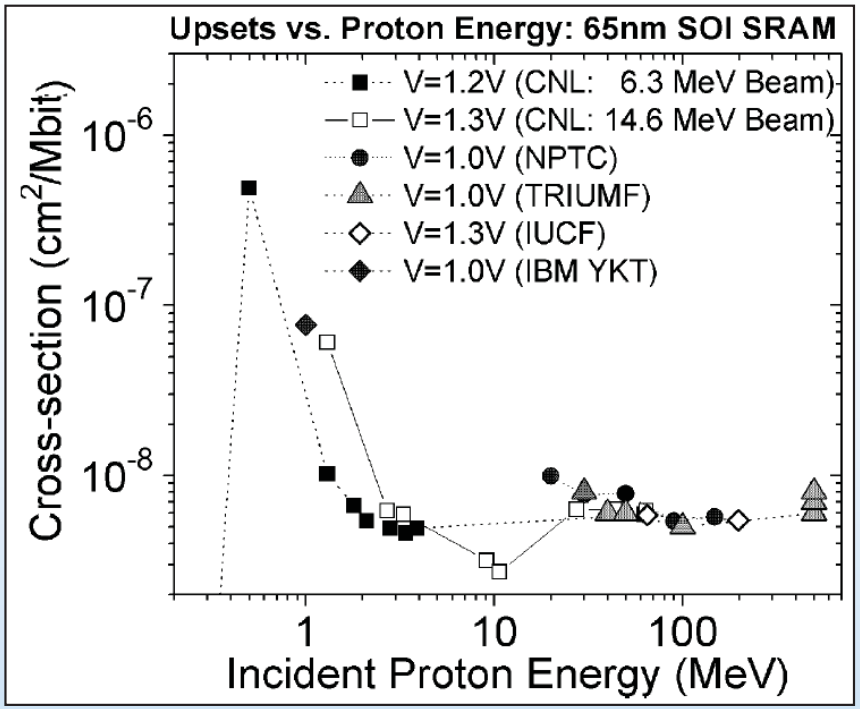
Outline

- Introduction
  - Low-energy protons (LEPs)
  - Test facility setup
- Protons vs. alphas
- DUT is 32 nm SOI CMOS 128 Mb SRAM
  - Heavy ion data baseline
  - DUT is in a flip-chip package
- SBU and MCU SRAM data
- Die thickness reverse engineering with SRIM
- Summary

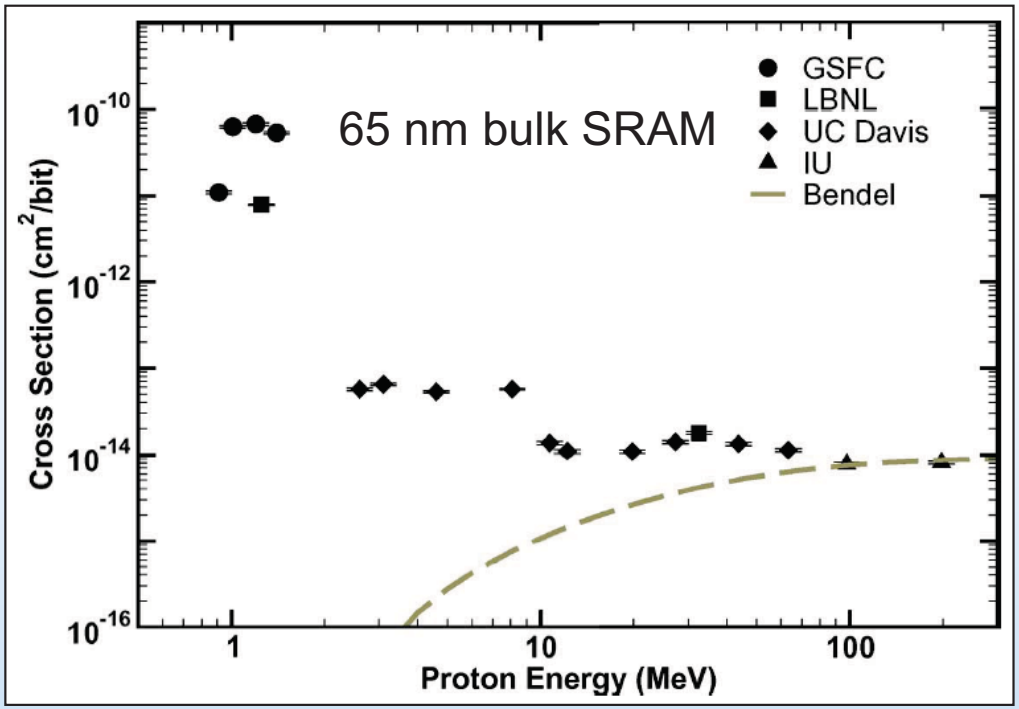
UC Davis CNL Test Setup



Early Low-Energy Proton Data



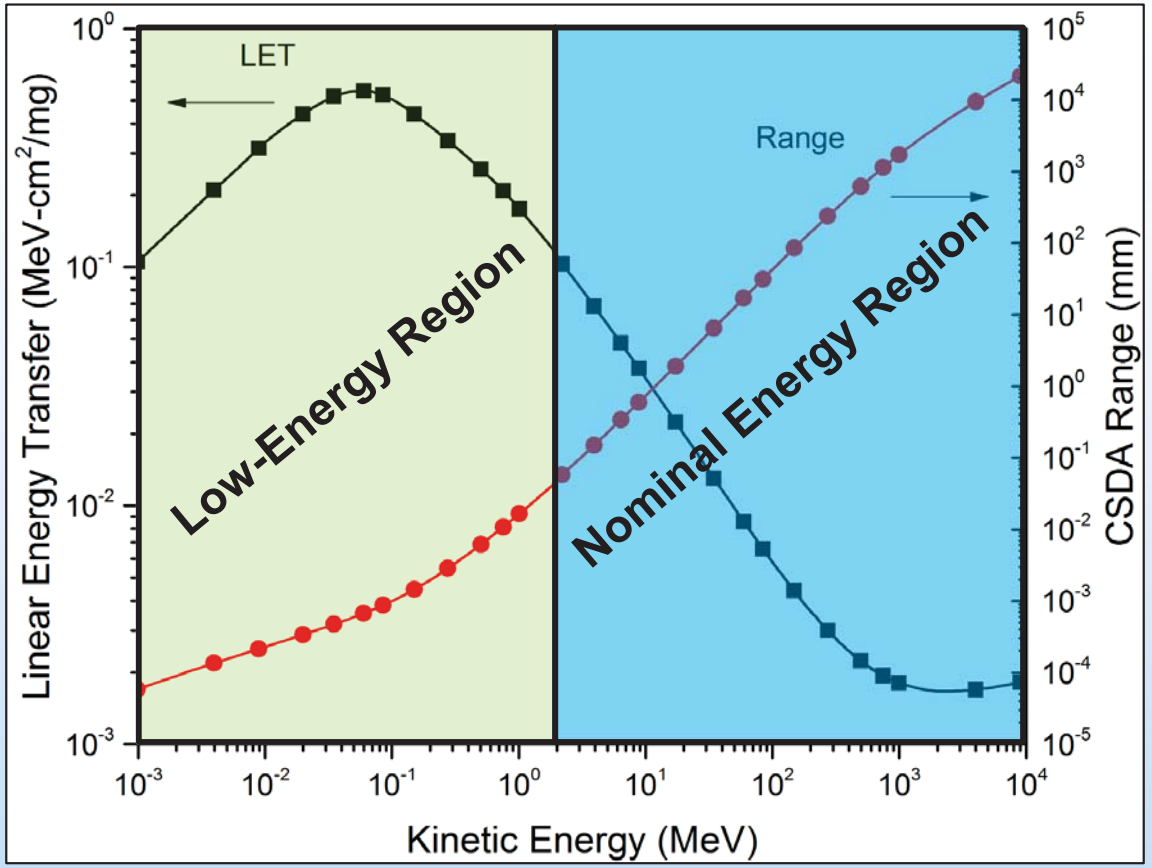
D. F. Heidel et al., IEEE TNS, vol. 6, 2008.



B. D. Sierawski et al., IEEE TNS, vol. 6, 2009.

- **Cross sections are plotted as a function of <u>incident</u> proton energy – inversely proportional to degrader thickness.**
  - **Several implications: changes to the energy distribution shape, flux depletion near end-of-range, etc.**
  - **Can plot data as a function of degrader thickness.**
- **How do we know the mean energy and standard deviation?**

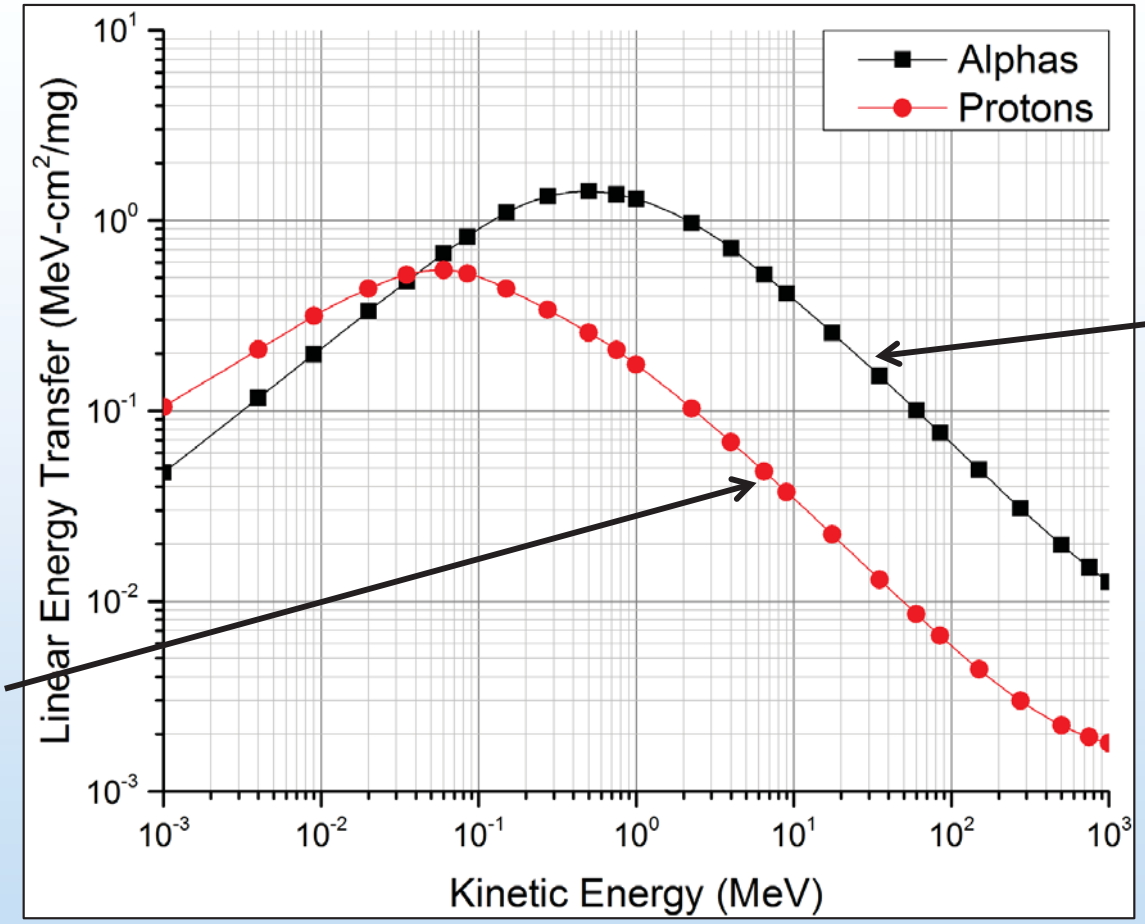
The Problem with LEPs – Range & d*E*/d*x*



NIST PSTAR tool (ICRU Report 49, 1993).

- **Greatest effect in the shortest distance**
- **Short range in region of interest implies flux depletion**
- **Cross sections tend to be uncorrected for flux loss and plotted as a function of known quantities (e.g., degrader thickness)**

The Alpha (^{4}He) Alternative



^{4}He starts at 30 MeV

H^+ starts at 6.5 MeV
- CNL uses ~13 MeV H_2^+ to generate LEPs

NIST ASTAR/PSTAR tool (ICRU Report 49, 1993).

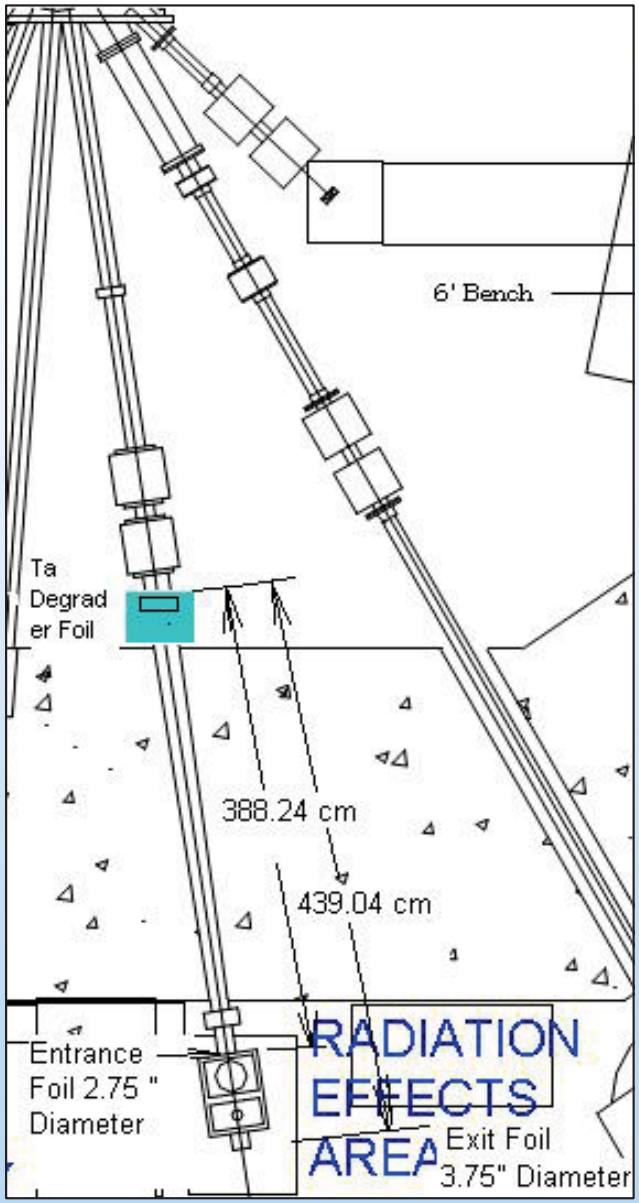
- **<u>Hypothesis</u>: Alpha particles can replace LEPs for direct ionization single-event effects testing.**

In the context of LEPs, mentioned as early as 2009 – B. D. Sierawski et al., including J. Pellish.

UC Davis Crocker Nuclear Laboratory

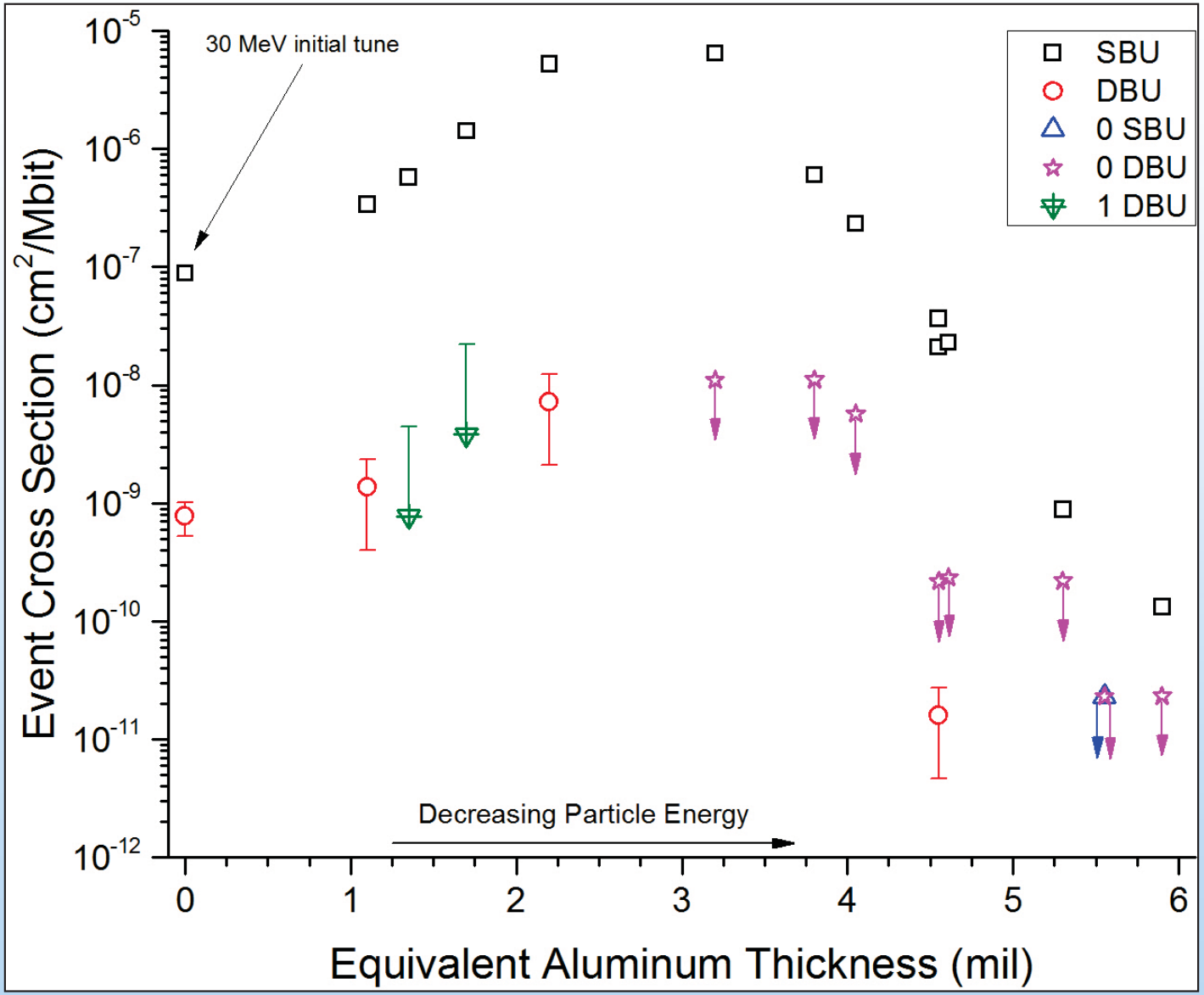
Assuming Setup In-Air (can do vacuum)

- **Beam diameter on 0.25 mil Ta foil is ~5/16 in.**
- **Defining collimator is 2.75 in with acceptance angle of 0.018 rad.**
- **Secondary electron emission monitor (SEEM) uses three 0.25 mil Al foils.**
- **User-selected degraders can be Al or Mylar.**
- **Exit window is 5 mil Kapton.**
- **Air gap is user-selected within experimental parameters.**



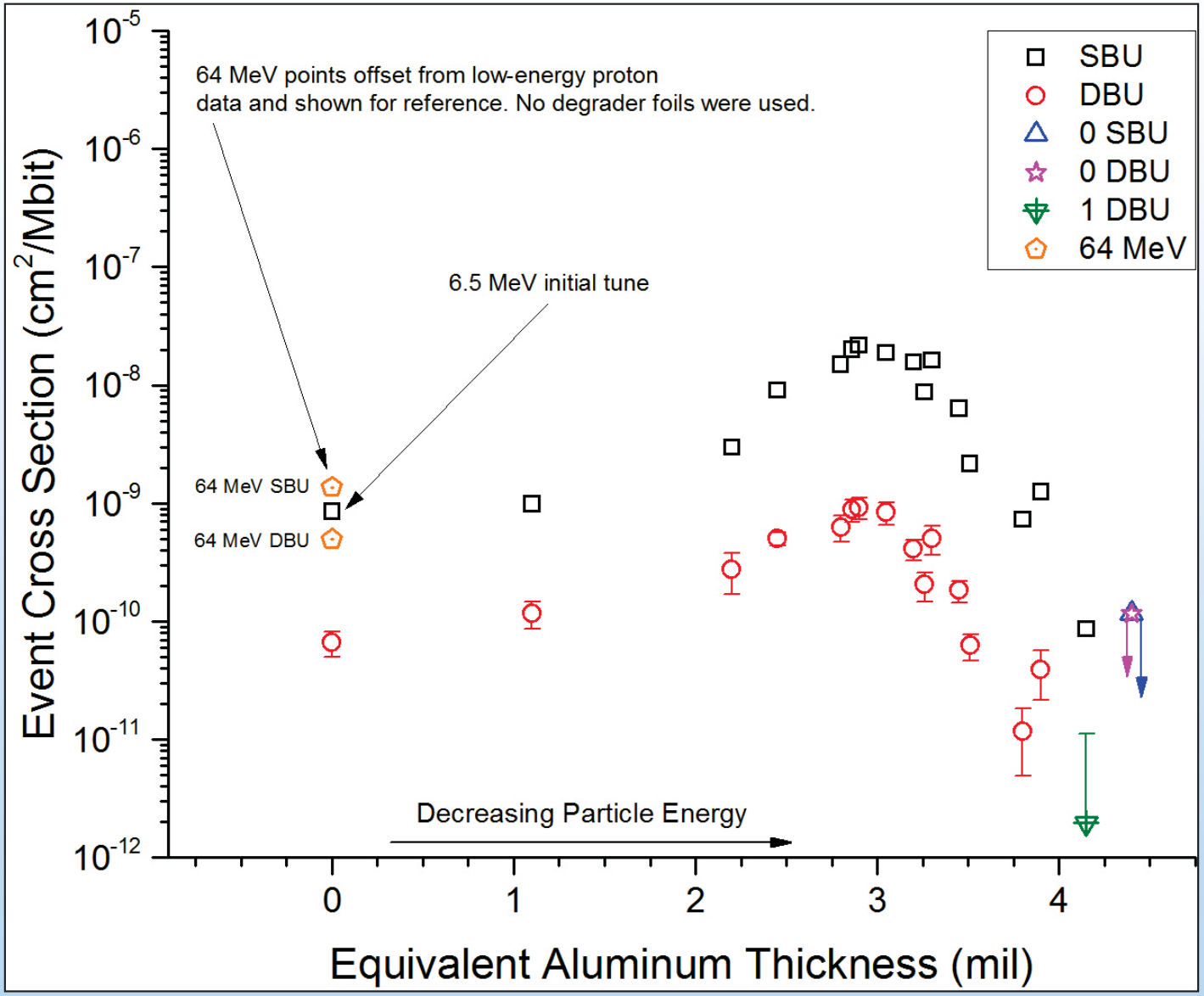
Courtesy of T. Essert and M. Van de Water (UCD/CNL).

30 MeV Alpha SEU Data 0x0000 Pattern



Error bars, if shown, are at the 90% confidence level.

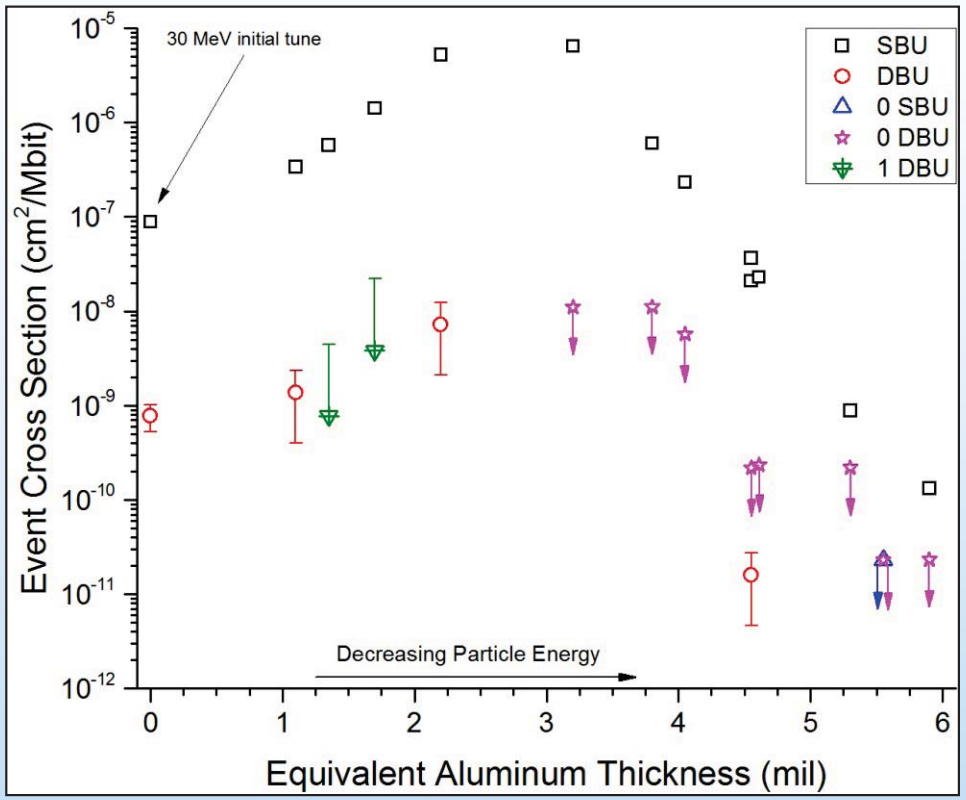
6.5 MeV Proton SEU Data 0x0000 Pattern



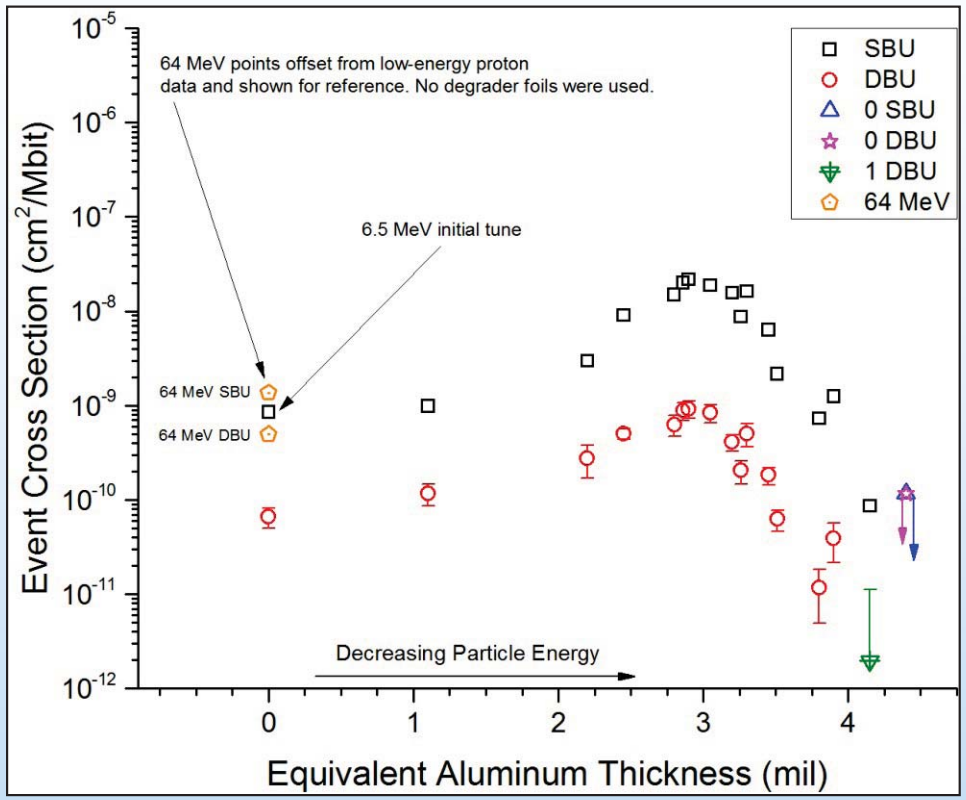
Error bars, if shown, are at the 90% confidence level.

Data Comparison – Side-by-Side

Alpha

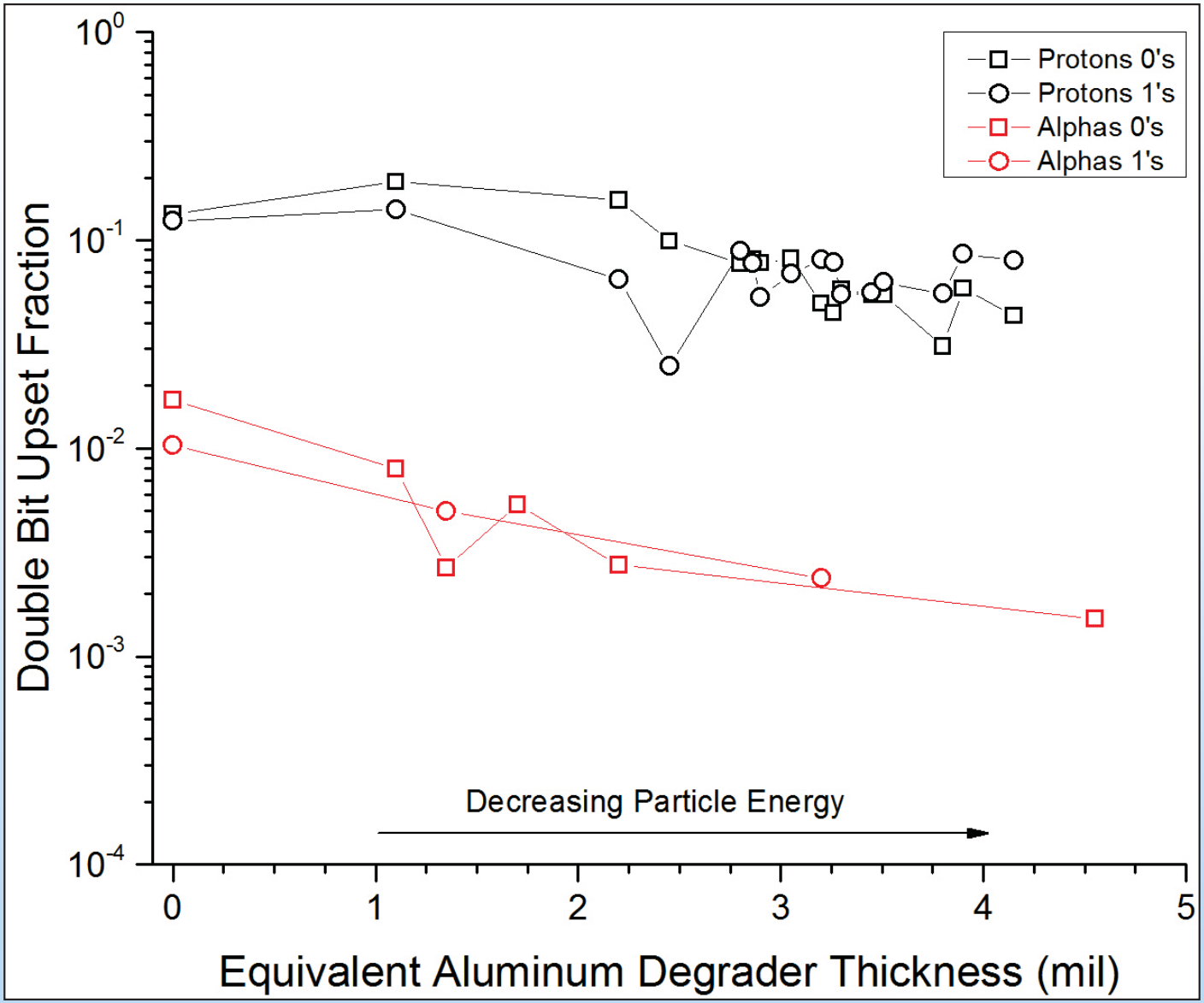


Proton



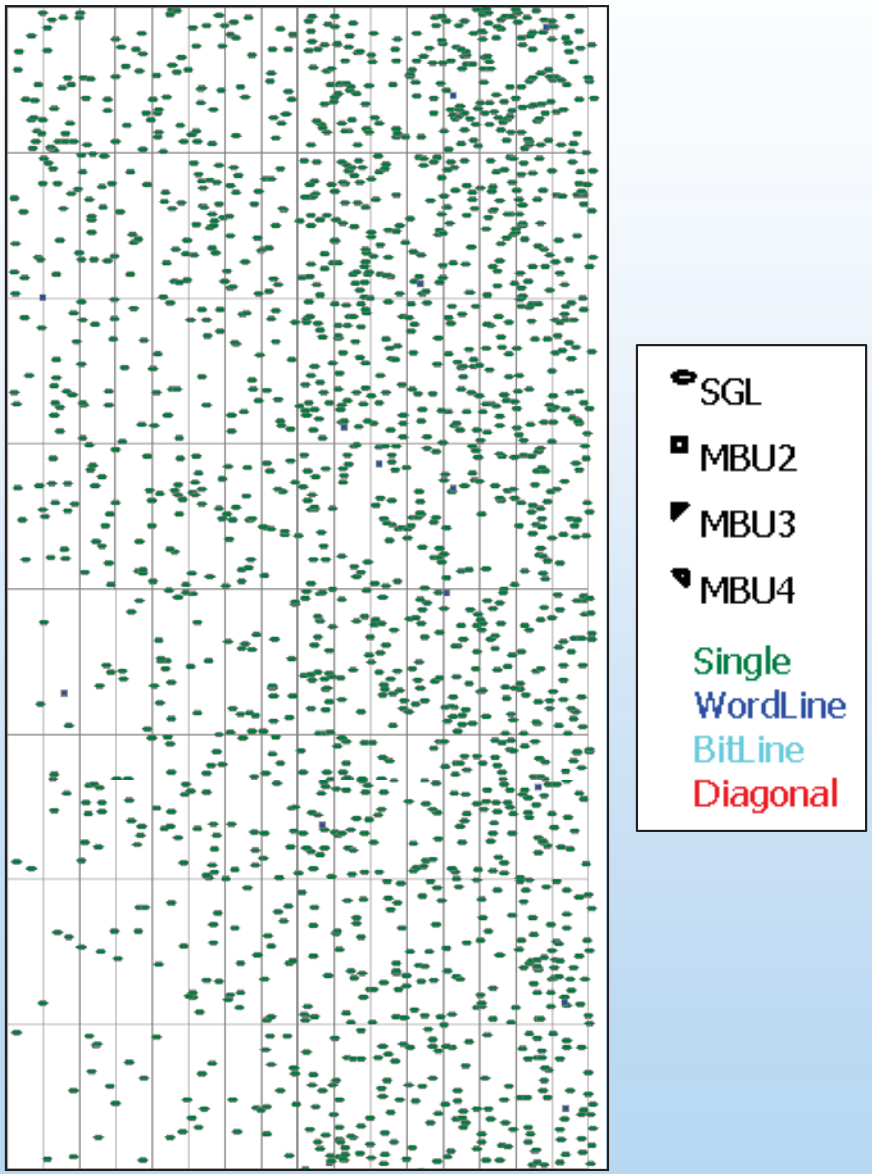
- On the low-energy side of the Bragg peak, the cross sections are similar, but the type of events are not.
- One of the key features is the separation between SBUs and DBUs.

Alpha & Proton DBU Fraction



Shows both 0x0000 and 0xFFFF data patterns.

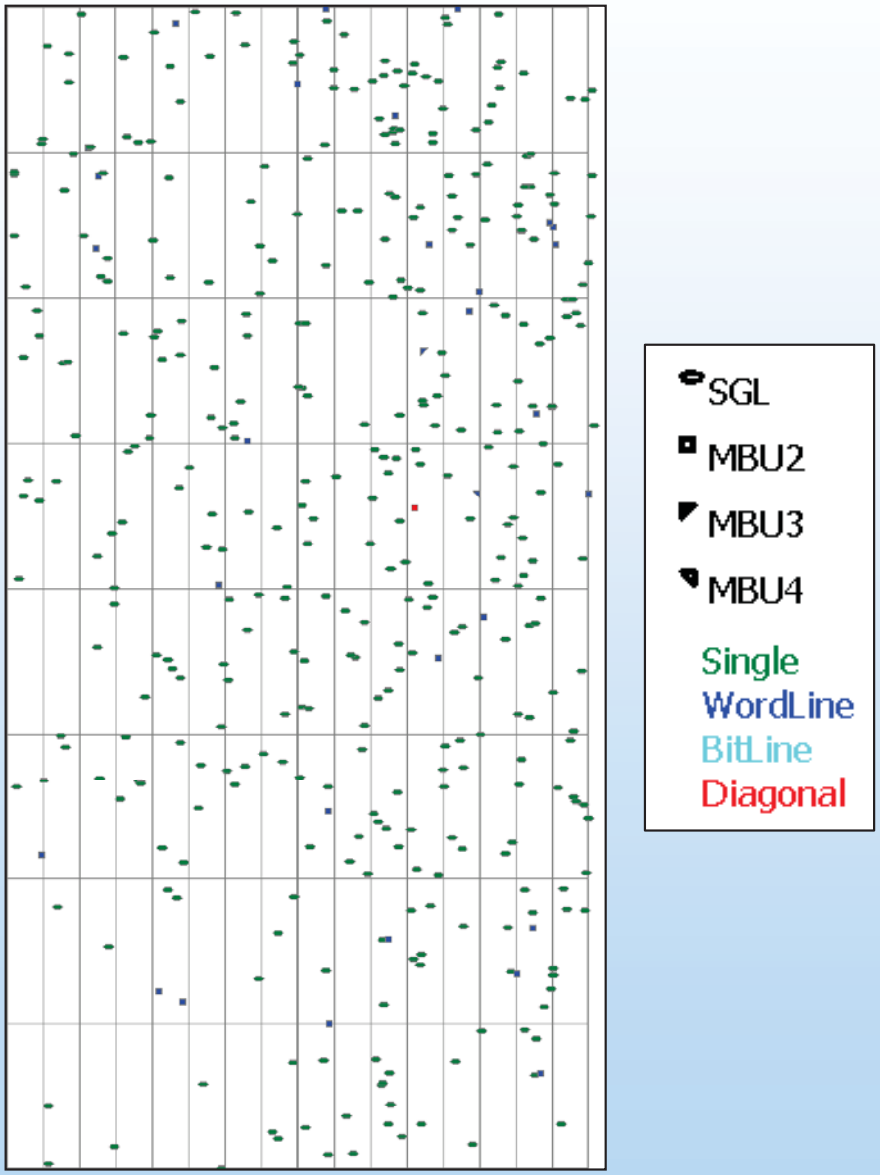
Physical Failure Maps – Alphas 0x0000 Pattern



In legend – MBU = MCU

- 30 MeV primary
  - No user degrader
  - Actual alpha energy below primary tune
- Only 14 total MCUs
  - All DBUs
  - 4 on left, 10 on right
- For alpha/proton comparison, remember, these plots are absolute event counts.
  - Total fluence and LET dependencies.

Physical Failure Maps – Protons 0x0000 Pattern

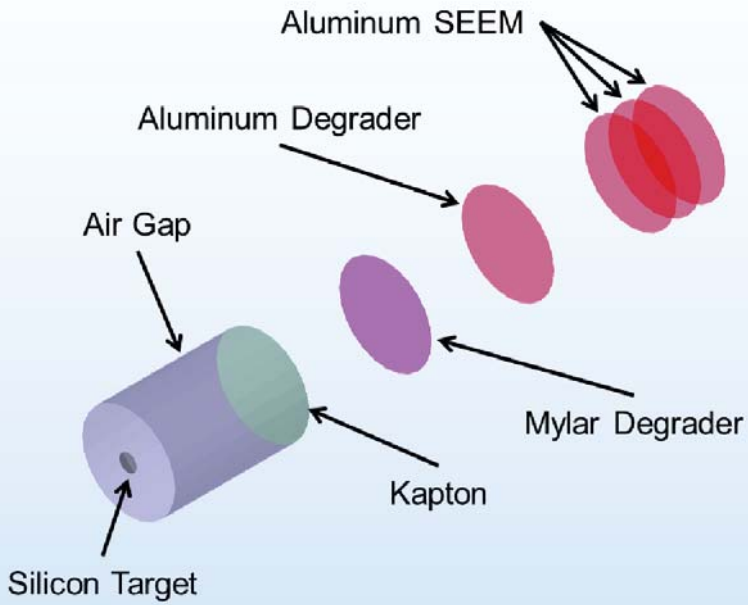


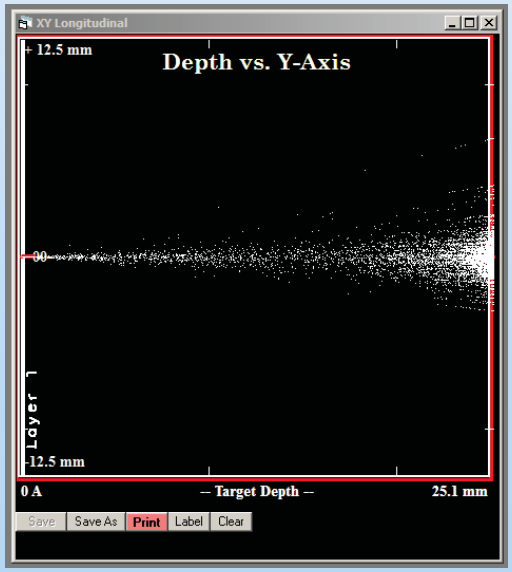
In legend – MBU = MCU

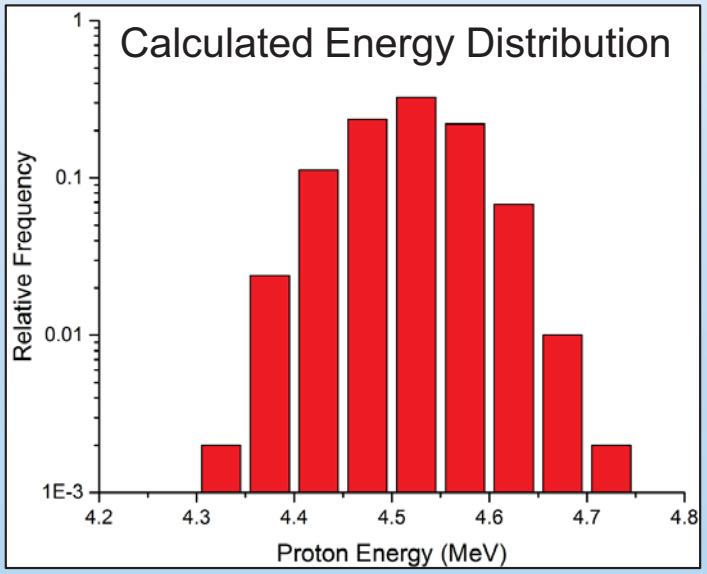
- 6.5 MeV primary
  - No user degrader
  - Actual proton energy below primary tune
- 32 total MCUs
  - 13 on left, 19 on right
- Most MCUs are word-line DBUs
  - One 3-bit MCU and one 4-bit MCU – both word line
- For alpha/proton comparison, remember, these plots are absolute event counts.
  - Total fluence and LET dependencies.

Incorporation of SRIM Simulations to Calculate Die Thickness

- **Fail mapping can be used to isolate areas of interest for analysis.**
- **Beam stopping degrader thickness can be used to "back out" silicon die thickness.**







Summary

- Low-energy proton testing is challenging.
- At this point, there appears to be no suitable proxy for the observed single-event effects produced by low-energy protons.
  - While alpha particle and proton SBU behavior seems to be proportional to LET, the MCU behavior is not.
    - There are subsequent implications for radiation hardness assurance.
  - May be more room for compromise at CMOS technology nodes > 65 nm.
- Additional analysis techniques presented to aid data reduction efforts.
  - Many technologies are flip-chip (such as our SRAM DUT), and die thickness uncertainty has always been one of the larger sources of systematic error.

Acknowledgements

- NASA Electronic Parts and Packaging Program
- Defense Threat Reduction Agency
- National Reconnaissance Office

Questions?